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REVIEW ARTICLE

A survey of unresolved problems in life cycle assessment

Part 1: goal and scope and inventory analysis

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Abstract
Background, aims, and scope Life cycle assessment (LCA) stands as the pre-eminent tool for estimating environmental effects caused by products and processes from 'cradle to grave' or 'cradle to cradle.' It exists in multiple forms, claims a growing list of practitioners, and remains a focus of continuing research. Despite its popularity and codification by organizations such as the International Organization for Standards and the Society of Environmental Toxicology and Chemistry, life cycle assessment is a tool in need of improvement. Multiple authors have written about its individual problems, but a unified treatment of the subject is lacking. The following literature survey gathers and explains issues, problems and problematic decisions currently limiting LCA's goal and scope definition and life cycle inventory phases.
Main features The review identifies 15 major problem areas and organizes them by the LCA phases in which each appears. This part of the review focuses on the first 7 of these problems occurring during the goal and scope definition and life cycle inventory phases. It is meant as a concise summary for practitioners interested in methodological limitations which might degrade the accuracy of their assessments. For new researchers, it provides an overview of pertinent problem areas toward which they might wish to direct their research efforts.
Results and discussion Multiple problems occur in each of LCA's four phases and reduce the accuracy of this tool. Considering problem severity and the adequacy of current solutions, six of the 15 discussed problems are of paramount importance. In LCA's first two phases, functional unit definition, boundary selection, and allocation are critical problems requiring particular attention.
Conclusions and recommendations Problems encountered during goal and scope definition arise from decisions about inclusion and exclusion while those in inventory analysis involve flows and transformations. Foundational decisions about the basis of comparison (functional unit), bounds of the study, and physical relationships between included processes largely dictate the representativeness and, therefore, the value of an LCA. It is for this reason that problems in functional unit definition, boundary selection, and allocation are the most critical examined in the first part of this review.

Keywords Environmental assessment · Goal and scope definition · Inventory analysis · LCA methodology · Life cycle assessment (LCA) · Life cycle inventory analysis (LCI) · Unresolved problems in LCA

Preamble This series of two papers reviews unresolved problems in life cycle assessment (LCA). Part 1 focuses upon problems in the goal and scope definition and life cycle inventory analysis phases. Part 2 (Reap et al. 2008) discusses problems in the life cycle impact assessment and interpretation phases. Having probed LCA's main weaknesses, Part 2 identifies critical problems and suggests research agendas meant to ameliorate them. Additionally, the second paper in the series brings closure to the review with a unifying summary.

Part 2 'Impact assessment and interpretation' follows in the subsequent issue.

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1 Introduction

As governments, corporations, and consumers become increasingly aware of the environmental impacts caused by products, processes, and systems, accurate environmen-

tal assessment becomes increasingly important. Effective improvement and utilization of life cycle assessment (LCA), a pre-eminent tool for estimating environmental effects, hinge upon identifying current problems that burden LCA. This two-part literature review gathers, lists, and concisely explains technical problems and problematic decisions in LCA. It highlights the most pressing problems and it suggests research and development activities meant to alleviate them. For those familiar with LCA, this review serves as a compact reference. It is also meant as an overview of problems of which new practitioners and researchers should be aware. Those seeking an introductory though detailed description of LCA should consult the US Environmental Protection Agency's LCA 101 document (SAIC 2006). Foundational and new literature sources contain a wealth of information for those interested in exploring particular problems in greater detail. It is hoped that, by compiling LCA's problems in two comparatively concise documents, this review aids in keeping practitioners clear of current methodological pitfalls and in focusing researchers committed to improving this valuable tool.

According to the International Organization for Standards (ISO), LCA is a method used to assess environmental aspects and impacts of products (ISO 1997, 2006a). Following the convention found in ISO 14040, the word 'product' refers to both tangible goods and service systems in this review. Environmental impacts generated by all parts of a product's life cycle, from acquisition of materials through manufacture to recovery or disposal, are considered. One divides LCA into four distinct though interdependent phases:

1. *Goal and scope definition* attempts to set the extent of the inquiry as well as specify the methods used to conduct it in later phases. One selects a product system, functional units, boundaries, allocation methods, and impact categories during this defining phase.
2. *Life cycle inventory analysis* defines and quantifies the flow of material and energy into, through, and from a product system (ISO 1998, 2006b).
3. *Life cycle impact assessment* converts inventory data into environmental impact estimates using a two-step process of classification and characterization (ISO 2000a, 2006b).
4. *Life cycle interpretation* marks the point in an LCA when one draws conclusions and formulates recommendations based upon inventory and impact assessment data. Iteration between life cycle interpretation and the other LCA phases often occurs.

ISO's structure for LCA provides a familiar means of organizing the problems discussed in this survey. In this review, descriptions of problems and problematic decisions are, therefore, organized according to the LCA phase in which each arises (Table 1). One should note that this organization differs, somewhat, with that found in ISO 14040 (ISO 1997, 2006a). For instance, allocation procedures are assigned during the goal and scope phase (ISO 1997, 1997, 2006a), but problems associated with allocation actually occur during inventory analysis. So, this review considers allocation problems in the section devoted to problems in inventory analysis. The "Goal and scope problems" section documents problems arising in the goal and scope phase while the "Life cycle inventory problems" section accomplishes the same task for the inventory phase. Part 2 addresses problems occurring in life cycle impact assessment (LCIA) and LCA's interpretation phase. It also covers data availability and quality.

Part 2 proceeds to identify the most pressing problems in LCA and to suggest research programs meant to ameliorate them. It also contains closing remarks meant to summarize and reflect upon both parts.

2 Goal and scope problems

Major problems in goal and scope definition occur as a result of three methodological choices. When comparing two or more different product systems in an LCA, functional unit definition and assessment boundary selec-

Table 1 LCA problems by phase

Phase	Problem
Goal and scope definition	Functional unit definition[a]
	Boundary selection[a]
	Social and economic impacts[a]
	Alternative scenario considerations[a]
Life cycle inventory analysis	Allocation
	Negligible contribution ('cutoff') criteria
	Local technical uniqueness
Life cycle impact assessment	Impact category and methodology selection
	Spatial variation
	Local environmental uniqueness
	Dynamics of the environment
	Time horizons
Life cycle interpretation	Weighting and valuation[a]
	Uncertainty in the decision process
All	Data availability and quality

[a] One might reasonably consider these problems to be pivotal decisions. Unlike the others, their partial dependence on study goals limits the capacity to generate solutions via scientific and technical consensus building. However, their strong influence on a study's outcome makes the inaccuracies introduced by an inappropriate decision high. It might, therefore, be more appropriate to think of these problems as problematic decisions

tion give rise to several difficulties. Additionally, the exclusion of social and economic aspects holds implications for LCA of which practitioners and researches should be aware. These problematic decisions differ from other problems discussed in this two-part review. Unlike the others, these problems are rooted in social as well as scientific and technical factors. Stakeholder desires imputed into a study's goal statement represent an injection of conflicting and ever changing social values. Such characteristics place these problems in a larger class of problems known as 'wicked problems' in environmental science (Norton 2005). The discussion of economic and social life cycle assessment in "Life cycle costs and social impacts" section serves as a case in point. A life cycle study with a strong focus on sustainability would find the lack of integration between life cycle costing and social life cycle assessment problematic. A study with an entirely environmental focus would not. Those conducted the latter study might even find a methodology that forces them to consider social and economic factors a hindrance. In both cases, the socially influenced goal of the study determines whether a problem emerges. The following sections emphasize the technical aspects of problematic decisions in LCA, but one must bear in mind that technical improvements cannot remove the need to make socially influenced decisions during goal and scope definition.

2.1 Functional unit definition

"A functional unit is a measure of the performance of the functional outputs of the product system" (ISO 1997). Its purpose is "to provide a reference to which the inputs and outputs are related… [and] …to ensure comparability of LCA results." Thus, adequately selecting a functional unit is of prime importance because different functional units could lead to different results for the same product systems (Hischier and Reichart 2003; Kim and Dale 2006).

Unfortunately, multiple potential sources of error can diminish confidence in the appropriate selection of a functional unit (Fig. 1). As shown in Fig. 1, error can stem from inaccurate reflection of the product system reality when identifying and prioritizing functions, defining the functional unit and defining the reference flow.

Many products have multiple functions (e.g., Internet, PDA, etc.) even though most products will tend to have a primary overall function. For instance, the overall function of a passenger car is to move people from point A to point B. However, moving people in a smoother and quicker sports car has additional and arguably relevant sub-functions that are somewhat different than those of a minivan or a mid-sized sedan. Hence, when crafting comparable LCAs for these types of products, it is important to consider these other sub-functions. Not identifying, decomposing, specifying, and/or prioritizing these functions appropriately with respect to a study's goal and scope might yield a functional unit that fails to reflect reality well.

In the second step of defining functional units, errors can arise when (1) assigning functional units to multiple functions, (2) carrying out strict, functionally equivalent comparisons, and (3) when handling non-quantifiable or difficult-to-quantify functions (Cooper 2003). The difficulty with assigning functional units to multiple functions is that various potential functional units may not address all functions, as is the case in metal cleaning industrial processes (Finkbeiner et al. 1997; Ruhland et al. 2000). The question for the LCA practitioner then becomes, "Which functional unit should I select and/or how do I assign the functional units appropriately to each function?" Cooper has noted three ways of handling this problem (Cooper 2003), which might conceivably lead to different LCA results. With strict, functionally equivalent comparisons, there is a danger that reality is not reflected well. This is illustrated well with one of the functional units used in a LCA study that compared the environmental impact of getting the news from different media such as a newspaper, TV, and the Internet (Hischier and Reichart 2003). In their study, the first functional unit strictly compared the impact of getting one news story. In the case of the newspaper, only the mass of the piece of paper containing the news story was compared against the other media. Obviously, this strict functional comparison does not reflect the fact that people do not get the newspaper in that fashion and thus can skew the results. Finally, when dealing with non-quantifiable or difficult-to-quantify functions, one defines functional units that serve as proxies or are more subjective

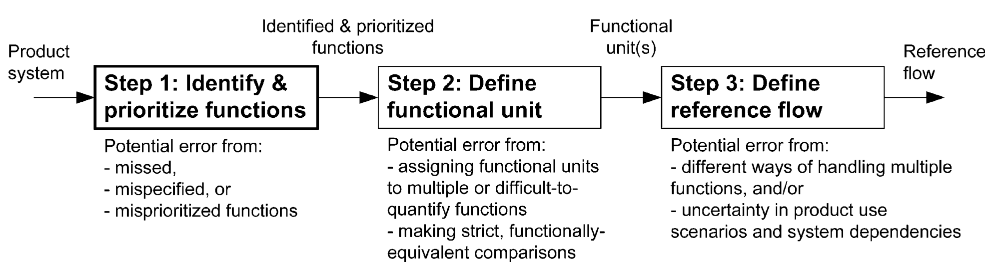

Fig. 1 Potential sources of error related to the functional unit

and, as a result, they are less comparable. Examples of these latter types of functions include the aesthetics of a product and the entertainment or learning a child gets from playing with a toy.

In the last step, error can arise from different ways to allocate reference flows to functional units (which will be addressed in the “Allocation” section) and what Cooper calls product lifetime, performance, and system dependency issues (Cooper 2003). Product lifetime and performance issues refer to uncertainties arising from different product use scenarios that affect the assumed lifetime and performance of the product and as such add variability or change the reference flow (Cooper 2003). System dependency issues refer to part-specific changes that affect other parts of the product system and, as a consequence, the whole system performance. The significance of these issues is that they can degrade the accuracy of the reference flows associated with the selected functional unit and thus decrease the confidence in the LCA results.

2.2 Unit process boundary selection

Boundary selection determines the processes and activities included in a LCA study. A product system’s unit processes, included life cycle stages, impacted geographic area and relevant time horizon influence boundary selection. This section discusses boundary selection for unit processes. The influence of time horizons on boundary selection is addressed in the second paper of this two-part series.

The basic problem centers on justifying one’s LCA study boundaries based on a more objective, repeatable, and scientific basis given time and resource constraints (Raynolds et al. 2000a; Suh et al. 2004). In other words, this entails considering the right amount of breadth and depth in one’s boundary selection to inspire enough confidence in the interpretation of the LCA results. The danger of not selecting appropriate boundaries is that LCA results may either (1) not reflect reality well enough and lead to incorrect interpretations and comparisons (Graedel 1998; Lee et al. 1995) or (2) provide the perception to the decision maker that it does not reflect reality well enough and thus lower his/her confidence in making decisions based on the results. A recent example of this problem can be observed in the debate surrounding the energy balance of ethanol where the selection of boundaries (like the inclusion of corn-based ethanol co-products or energy from combustion of lignin in cellulosic ethanol) can change the results significantly (Farrell et al. 2006; Hammerschlag 2006). Another example is leaving out maintenance and auxiliary activities such as floor cleaning, stripping, and waxing, which are likely to release more volatile organic carbon emissions (by several orders of magnitude) than the release occurring during a floor’s 72-h post-installation period (Lent 2003).

2.2.1 Problems with ISO 14041’s approach to boundary selection

To address the boundary selection problem, ISO 14040: 2006(E) standards recommend that the decision to select “elements of the physical system to be modeled” be based on: the goal and scope of the study, the application and audience, assumptions, constraints, and some ‘cutoff criteria’ that is “clearly understood and described” (ISO 2006a). The recommended ‘cutoff criteria’ includes the contribution of the element to the total mass, energy, or environmental relevance of the studied system. Overall, it suggests that an initial system boundary be selected and that iterative refinements be made by including new unit processes shown to be significant via sensitivity analysis (Suh et al. 2004).

Many researchers have criticized the amount of subjectivity allowed by the ISO standards, which could lead to less confidence in comparative LCA study results (Suh et al. 2004). Specifically, various researchers have argued that a cutoff is very difficult to justify even when using ISO’s criteria (Raynolds et al. 2000a; Suh et al. 2004). For instance, the following criticisms have been put forward by Suh and coauthors (Suh et al. 2004):

1. “there is no theoretical or empirical basis that guarantees that a small mass or energy contribution will always result in negligible environmental impacts,”
2. some input flows bypass the product system and do not contribute mass or energy content to the product,
3. “environmental impacts by inputs from service sectors cannot be properly judged on the basis of mass and energy,”

and

4. while the individual inputs and outputs cutoff may be insignificant, their total sum might change the results considerably.

Essentially, a boundary selection cutoff introduces a truncation error. A cutoff ideally would be based on the percentage of an aggregated impact score and/or different impact category indicators of interest. Using this cutoff, however, is very difficult in practice because it requires that the LCA practitioner have a perfect, holistic knowledge of all the possible effects a decision might have on the product system and consequently on the impacts of interest. To reach a reasonable approximation of this perfect, holistic knowledge, a LCA practitioner will need to have access to relevant data and LCA studies or be focusing on a simple product system.

The first set of conditions will not hold for new technologies (e.g., nanotechnologies) or when a study report uses undisclosed confidential LCI data. Additionally, one might ask, if a practitioner has gathered all the data needed to establish a cutoff, why not use all of it?

2.2.2 Problems with other approaches to boundary selection

In addition to ISO's approach, several other researchers proposed or identified general ways to address the boundary selection problem. These approaches roughly belong to one of four categories: qualitative or semi-quantitative approaches, quantitative approaches guided by data availability, quantitative process-based approaches that use more refined cutoff criteria (Raynolds et al. 2000a, b), and input–output (IO) based approaches (Hendrickson et al. 1998; Hertwich 2005; Suh 2004; Suh and Huppes 2005; Suh et al. 2004).

Raynolds and coauthors examined the first two types of approaches and criticized them for being highly subjective, unrepeatable, or unscientific (Raynolds et al. 2000a). Process-based approaches that use more relevant cutoff criteria and progressively span outwards to include more unit processes on the other hand, while being more rigorous and repeatable, have been shown to yield potentially high truncation errors in the fossil fuel consumption of upstream production processes of many commodities (Lenzen 2000). They also dramatically increase the data needs as the boundary expands. In his study, Lenzen showed that for fossil fuel consumption of various commodities in Australia, errors ranged from 9% to 100% of the total using IO analysis (Lenzen 2000). Additionally, using process-based approaches usually excludes or cuts off capital goods, which some researchers have recently found can have a significant effect on environmental impacts results (Frischknecht et al. 2007; Mongelli et al. 2005). The limitations of process-based approaches have led many researchers to explore IO LCA-based approaches as a more comprehensive and faster way of selecting boundaries. IO LCA-based approaches have become popular in the last decade or so. A notable example is Carnegie Mellon's well-known Environmental Input–Output Life Cycle Assessment, which has been used by thousands of users from many different countries (Matthews and Small 2001). Other IO LCA-based methods include the so-called hybrid approaches discussed by Suh and coauthors (Suh et al. 2004). However, this family of IO LCA-based methods, in general, suffers from the following difficulties:

- The IO portion assumes that the amounts of imported commodities to the product system under study are negligible or that they come from countries with similar production technologies and economic structures (Suh 2004, p. 456), an assumption that Lenzen has conjectured could be off by a factor of three for some commodities[1] and which sounds questionable when considering that many products come from developing countries that have different electricity grid mixes, production technologies, and overall economic structures.
- There is lack of applicable, well-balanced sectoral environmental data in most countries that can be correlated with economic data (Suh and Huppes 2005).
- The IO-based data is usually several years older than process-based data; so it may be somewhat outdated for industry sectors that change technologies often.
- The IO-based data is usually aggregated for industries and commodities, thus diminishing the resolution capability of the IO analysis when compared with more detailed LCAs. The IO-based data assumes companies are perfectly homogeneous, meaning that they produce only one commodity and as such there is an allocation error.
- Some assume that monetary and physical flows are equivalently proportional amongst different industries, whereas the proportionality constants or multipliers vary between and within industries (Lenzen 2000).
- There is some uncertainty in the economic data collected from surveys to create the national economic IO tables (Lenzen 2000).
- Many IO LCA-based methods do not consider 'gate-to-grave' industrial processes so they carry a truncation error themselves. Some researchers have claimed this error may be negligible in many instances (Lenzen 2000; Peters and Hertwich 2006), but other researchers caution that a quick elimination without further study may lead to neglecting significant unit processes (Suh 2006).
- Many IO LCA-based methods do not seem to consider the recycling (Bailey et al. 2004a, b) or remanufacturing industry sectors (Ferrer and Ayres 2000).
- It is unclear where the border between the IO-based and process-based data should be drawn when using integrated hybrid analysis (Suh et al. 2004) and if data should be fed back to the IO-based assessment at all (Hertwich 2005).

Given the potentially high investment involved in carrying out a LCA and all the debates surrounding its accuracy, a well-justified and transparent selection of boundaries is warranted to add credibility or confidence to the LCA results. On the other hand, increasing confidence

[1] Calculated from the difference in the energy multiplier to assemble (4 MJ/\$) and produce vehicle and parts (12 MJ/\$) (Lenzen 2000, p. 137).

in selecting appropriate boundaries might require a great deal of data, which might unnecessarily increase the costs and time of the LCA study with very little to no value added (Graedel 1998). Therefore, we believe this is still an area where more research is needed to provide clear practical guidelines, appropriate information, and tools to support boundary selection in LCA practice.

2.3 Life cycle costs and social impacts

In addition to environmental impacts, product systems cause economic and social impacts during their life cycles. LCAs, however, traditionally focused only on environmental impacts, and ISO documentation limits LCA's purview to environmental effects (ISO 2006a, b). As a consequence, some researchers note that, "…recommendations based on LCA fail to address possible trade-offs between environmental protection and both social and economic concerns in the product life cycle" (Dreyer et al. 2006). From a sustainable development perspective, this can limit the capability of LCA to support decisions from both the perspective of sustainable production (i.e., companies desiring to be more sustainable) and sustainable consumption (i.e., governments developing policy to reduce unsustainable consumption trends) (Hertwich 2005). From a purely economic perspective, Norris notes that the consequences of not integrating environmental and economic assessments can be missed opportunities or limited influence of LCA for decision making, especially in the private sector (Norris 2001). This is because analysts are less able to capture relationships between environmental and cost consequences of alternative decisions.

In response, various researchers have tried to resolve this problem by finding ways to integrate LCA with elements and methodologies for social impact assessment (Dreyer et al. 2006; Hunkeler 2006; O'Brien et al. 1996) and life cycle costing (LCC) (Emblemsvag and Bras 2001; Hunkeler and Rebitzer 2003; Norris 2001). Unfortunately, integrating LCC and LCA is difficult, but probably even more so when integrating social assessments (Hunkeler and Rebitzer 2005). Integration attempts are fraught with difficulties summarized in Table 2.

Even the concept of 'integration' is unclear in this context. On one extreme, one might develop a federated life cycle tool that models environmental, economic, and social consequences in a tightly integrated framework. On the other, one might argue that LCA should remain a largely independent method that only shares a few, key structural elements such as a system boundary when used in conjunction with separate LCC and social-LCA methods.

Table 2 Difficulties in integrating social aspects and LCC with LCA

Problems		Reference
Social	No consensus on how to integrate and calculate social impacts of products since social impact methodologies are still in their infancy	(Hunkeler 2006; Rebitzer and Hunkeler 2003)
	More than 200 societal midpoint impact indicators exist, which may lower probability of obtaining agreement on their selection and valuation in actual use	(Hunkeler 2006; Hunkeler and Rebitzer 2005)
	Most impacts on people are independent of the physical processes that make the product and more dependent on company behavior and as such the "relation of the impacts to the product…is no longer straightforward"	(Dreyer et al. 2006)
	Integrating social impact assessment qualitative approaches and data with LCA may be problematic	(O'Brien et al. 1996)
	Data needs are greatly increased with non-environmental, company-specific data or region-specific data	(Dreyer et al. 2006; Hunkeler 2006)
Economic	LCC analysis is not within the scope of developed LCA methodology, or properly addressed in traditional LCA tools, or by ISO 14040	(Norris 2001)
	"…there is neither scientific nor procedural agreement between the various stakeholders regarding [LCC] terminology, methodology, data formats, reporting, etc."	(Rebitzer and Seuring 2003)
	Disagreement on how to handle externalities in light of taxes and subsidies in order to avoid double counting (e.g., carbon taxes)	(Rebitzer and Hunkeler 2003)
	Disagreement on how to assign costs to different stakeholders (e.g., the cost to the consumer buying a product is the revenue of a company)	
	Disagreement on how to estimate and discount future costs and revenues	
	How to align data per functional unit with financial data	(Hunkeler and Rebitzer 2005)
	How to use the same system boundaries (e.g., the time horizon of an LCC might be shorter than the one assumed for a LCI and LCIA)	(Hunkeler and Rebitzer 2003; Norris 2001; Rebitzer and Hunkeler 2003)

Complexity and cost appear to be the federated approach's primary limitations. The potential to miss important relationships might limit the latter approach and selection of key common structural elements may prove less than straightforward. Clearly, more research and open debate are needed to determine the extent to which it is feasible, valid, and beneficial to integrate LCA with LCC and emerging social impact methodologies in light of the new problems brought by integration.

2.4 Alternative scenario consideration

"A scenario in LCA studies is a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future" (Pesonen et al. 2000). Some examples of scenarios that could be used in a LCA study include end-of-life scenarios (e.g., 20% landfill, 40% open-loop recycling, and 40% incineration), changes in technology (e.g., from solvent-based to aqueous-based cleaning), etc. (Pesonen et al. 2000). Obviously, the scenarios a LCA practitioner assumes for the LCA study will influence the results. In fact, the scenarios considered will influence all the following phases of LCA. For these reasons, it is important to select appropriate scenarios.

The inherent difficulty with any formal scenario analysis framework is that of trying to predict with confidence the future. As Smil notes, "…for more than 100 years long-term forecasts of energy affairs—no matter if they were concerned with specific inventions and subsequent commercial diffusion of new conversion techniques or if they tried to chart broad sectoral, national, or global consumption trends—have, save for a few proverbial exceptions confirming the rule, a manifest record of failure" (Smil 2003). Given that this 'record of failure' just focuses on energy affairs, any LCA practitioner should pause and carefully reflect on the scenarios selected and the level of detail used in predicting the potential scenario conditions since they may "engender false feelings of insight…" (Smil 2003).

Other researchers have noted some practical problems associated with the consideration of scenario alternatives. For example, some observe that LCA studies usually do not consider the 'zero' or null alternative (Hauschild and Wenzel 2000). The 'zero' or null alternative means the scenario where the decision being evaluated is not carried out (i.e., the 'business as usual' scenario). Null scenarios define a baseline and help recipients of LCA studies see the advantages and disadvantages of a proposed change. In the latter case, they even allow those involved in the decision process to claim 'credit' for impacts potentially avoided by inaction. Another issue that has been noted in the literature is the fact that the scenarios underlying LCA studies are often not explicitly defined (Pesonen et al. 2000).

3 Life cycle inventory problems

Problems specific to life cycle inventories revolve around material flow, energy flow, and process modeling. Where the goal and scope phase presented problems associated with setting study parameters, the inventory phase presents problems associated with finding and setting modeling parameters. First and foremost among these is the problem of allocation. The criteria used to identify and eliminate ('cutoff') unimportant resource and waste flows to and from an activity present another noteworthy difficulty. A lesser, though important, problem is that of local technical uniqueness. Data quantity and quality problems are discussed in Part 2.

3.1 Allocation

The allocation problem has the distinction of being called one of the most controversial issues of LCA (Rebitzer et al. 2004) and "one of the classical methodological problems in LCA" (Russel et al. 2005). Allocation refers to the procedure of appropriately allocating the environmental burdens of a multi-functional process[2] amongst its functions or products. Thus, from this perspective, the allocation problem is one of determining how much of the environmental burdens caused by the multi-functional process should be apportioned to each product or function even though other researchers have suggested a different definition[3] (Heijungs and Frischknecht 1998). Obviously, arbitrary allocations could lead to incorrect LCA results and less preferable decisions based on those results. Compounding this problem is the fact that many solutions have been suggested and applied to the allocation problem (Ekvall and Finnveden 2001; Russel et al. 2005). Ekvall and Tillman mention eight allocation procedures that they considered fair or reasonable based on the procedures'

[2] Examples of multi-functional processes requiring allocation include: incinerators, landfills, sawmills, dairies, oil refineries, metal smelting, transportation, etc. (Ekvall and Finnveden 2001).

[3] Heijungs and Frischknecht have suggested that the allocation problem arises from the fact that when one models the unit processes used in the LCI assessment as a technology matrix, many times the matrix cannot be inverted and its pseudo-inverse does not yield an exact solution to the problem. From this perspective, which seems to apply only to descriptive closed-loop recycling cases where the technology matrix is square (i.e., the number of unit processes equals the number of balances), "…it is the database itself, the collection of process data that is used for finding the inventory table for any functional unit, that can create the allocation problem…independent of the case study at hand." (Heijungs and Frischknecht 1998).

underlying perspectives (Ekvall and Tillman 1997). More recently, in her review of allocation approaches, Curran concluded that no single method provides a general solution (Curran 2007). For LCA practitioners searching for an optimal procedure, learning these conclusions and finding this many proposed allocation procedures might prove frustrating. This could result in hasty selections of allocation approaches which, in turn, lead to incorrect or incomparable LCA results.

Thus, to deal with the allocation problem, ISO recommends that LCA practitioners follow the following stepwise procedure (ISO 1998, 2006b):

1. Avoid allocation when possible by (1) dividing the unit processes into sub-processes and gathering the required environmental burden data and/or (2) expanding the product system boundaries to include additional functions related to the co-products.
2. If allocation cannot be avoided, allocate the environmental burdens of each product based on their underlying physical relationships.
3. If allocation based on physical relationships cannot be done, allocate the environmental burdens of each product based on other relationships.

ISO provides additional recommendations for reuse and recycling scenarios primarily because more than one product system shares the burdens associated with extraction, processing, and disposal and the inherent properties of materials may change (ISO 2006b). ISO recommends using a closed-loop allocation procedure for both "'closed-loop product systems' and 'open-loop product systems' where no changes occur in the inherent properties of the recycled material" (ISO 2006b). For the latter scenario, they reason that recycling materials with constant inherent properties into another product system is equivalent to recycling it back into the original product system studied. Recycling displaces virgin material in both cases. Essentially, this assumption avoids expanding the system boundary by simplifying the allocation effect of recycling materials that do not change properties when recycled. If material properties change during recycling, then ISO recommends using an open-loop allocation procedure. In general, it recommends that the allocation procedures use, as a basis for allocation, the following criteria in the following order: physical properties like mass, economic value, or the number of subsequent uses of the recycled material.

The sections "Problems with avoiding allocation by subdivision or system expansion", "Problems with allocation procedures based on physical causality", and "Problems with allocation procedures based on non-causal relationships" discuss the limitations and difficulties associated with each of the recommended ISO steps in light of the reviewed literature and consequential LCAs.

3.1.1 Problems with avoiding allocation by subdivision or system expansion

When subdividing multi-functional processes, Ekvall and Finnveden conclude that subdivision can help reduce, though rarely eliminate, allocation problems because these processes are not likely to consist of physically separate single-function sub-processes (Ekvall and Finnveden 2001). They further assert that only if the sub-processes are physically and economically independent of each other will subdivision result in accurate information regarding the consequences of actions that have a significant effect on the production volume of the internally used function. In the case of open-loop recycling, they assert that subdivision will not reflect the consequences of any action very effectively in primary material production or final waste management because they affect multiple products and any action affecting one function will affect others (Ekvall and Finnveden 2001).

In the case of system expansion, "…the boundaries of the system investigated are expanded to include the alternative production of exported functions"[4] (Ekvall and Finnveden 2001). Azapagic and Clift state "there are two essentially equivalent system expansion approaches," namely direct system enlargement and the avoided burdens approach (Azapagic and Clift 1999a). They either add or subtract the environmental burdens of alternative ways of producing the product or co-products to make them comparable as shown in the theoretical multi-output case in Fig. 2.

The problem with these system expansion approaches is that they rely on (1) the existence of alternative production systems and (2) reliable and accessible inventory data for these production systems (Azapagic and Clift 1999a). If these two conditions could be commonly met in LCA studies, then the allocation problem could be avoided for a wide range of allocation problems via system expansion (Ekvall and Finnveden 2001). However, Ekvall and Finnveden suggest that system expansion should occur if the impact of the evaluated decision on indirect effects[5] is expected to significantly influence the LCA results. The problem here is: *how do you know if the influence will be significant if you do not have the data?* To determine the significance of the effects, one needs to learn if (1) the explored changes significantly affect the exported functions or co-products, (2) the exported functions or co-products significantly affected other external product systems, and (3) the uncertainty on both the external product system

[4] Exported functions refer to functions or co-products that are exported internally or externally of the product system studied.

[5] Indirect effects refer to the effects that decisions in the product system of interest will have on other product systems.

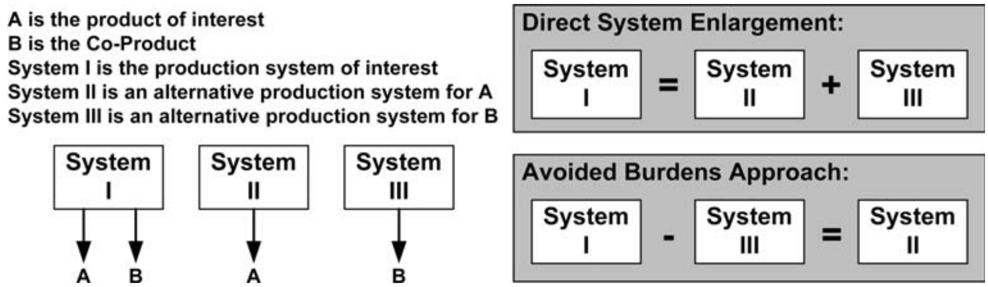

Fig. 2 Two different, equivalent ways to expand systems to avoid allocation

inventory data and the effect from the exported function or co-product is not too large (Ekvall and Finnveden 2001). All of this seems to be reinforced by Curran who notes that while system expansion is the preferred approach to deal with allocation problems, because it avoids allocation altogether, it leads to a larger, more complicated model that requires more data (Curran 2007). This also seems to be the case with Weidema's proposed allocation procedure, which is based on identifying the determining co-product[6] for the multi-functional process in question, determining the level of utilization of the dependent co-products and determining their level of displacement of other products in order to establish an allocation of the burdens to each co-product.

In either case, whether trying to reduce or avoid the allocation problem through subdivision or system expansion, more data needs to be collected (if it exists, is reliable, or is available) for relevant unit processes, which leads to more time, cost, and potential data quality uncertainty.

3.1.2 Problems with allocation procedures based on physical causality

If the allocation problem remains after subdivision and/or system expansion, the allocation of the remaining environmental burdens should be carried out using causal, physical relationships. In the LCA community, there seems to be a general agreement on the guiding principles recommended by ISO, particularly referring to the principle that allocation should be based on the underlying causal physical relationships (Azapagic and Clift 1999a; Ekvall and Tillman 1997; Finnveden 2000). Despite this general agreement, however, Finnveden notes the example of chlorinated dioxins emitted from incinerators where there are two scientifically based ways to establish causality (based on chlorine content of input materials/products or their heat value) that could yield significantly different results (Finnveden 2000). Finnveden considers this an example of a knowledge gap that introduces uncertainty due to lack of scientific understanding of the process, although Azapagic and Clift consider this an example of material-related and process-related causalities (Azapagic and Clift 1999b). Regardless of viewpoint, some unit processes possess causal relationships that are not completely understood, and if a LCA practitioner wishes to use these relationships, he will likely need more information to make a more appropriate allocation.

3.1.3 Problems with allocation procedures based on non-causal relationships

If the allocation problem remains after subdivision and/or system expansion and if causal, physical relationships have not been used to allocate the remaining internal functions, then non-causal relationships should be used. These relationships could be based on energy or exergy content, mass, volume, economic value, etc. (Ekvall and Finnveden 2001). Several reasons for using these relationships instead of causal relationships are: (1) lack of data or scientific knowledge, (2) convenience, the data is readily available or easier to get, and/or (3) the relationship may coincide with causal, physical relationships (e.g., when the ratio of outputs to inputs is fixed by stoichiometry; Azapagic and Clift 1999a). Nevertheless, various researchers note that these relationships might "…not accurately reflect the effects of actions" (Ekvall and Finnveden 2001) and that they have generally been discredited for lack of justification. Despite these warnings from the LCA research community, non-causal relationships seem to be the predominant allocation method used in LCI practice (Ekvall and Finnveden 2001).

3.2 Negligible contribution criteria

Even when an activity falls within the boundaries of a study, not all physical flows associated with such an activity are modeled. One justifies such exclusions by arguing that they make a negligible contribution to a product's environmental profile. In LCA, one refers to the rules used to judge insignificance as 'cutoff' criteria. Many

[6] The determining co-product is the product that has the single most influence regarding the inputs and outputs of the process. This influence may be due to the fact that it provides the most revenue, has a large market demand, is the only avenue of processing the co-product, etc.

difficulties associated with cutoff criteria for boundary selection also apply to cutoff criteria for resource and waste flows (see also the section "Problems with ISO 14041's approach to boundary selection"). In particular, small mass or energy flows may still cause noticeable impacts and the sum of individually insignificant flows may prove significant (Suh et al. 2004). Truncating models of physical flows in a product system threatens to omit burdens with the potential of generating decision-altering impacts.

3.3 Local technical uniqueness

Extraction, production, distribution, and end-of-life technologies used during a product's life cycle can vary with location. This local technical uniqueness affects the types and amounts of resources demanded and wastes produced by transformation of these resources. Environmental stressors associated with input resources change with employed technology; the burdens associated with electricity use, for instance, vary according to the mix of generation facilities supplying a region's grid. With regard to transformative processes, technology differences between regions, firms, facilities, and even production lines within facilities can lead to order of magnitude differences in emissions (Finnveden 2000). Despite the dependence of physical flows on the particular processes and technologies utilized at different locations, some inventories rely upon generic process descriptions that differ with those used in practice (Ayres 1995). In this sense, local technical uniqueness is a specific type of data quality problem (see Part 2). Ignoring these differences reduces the accuracy of such inventories.

4 Summary

This paper gathered, categorized, and discussed problems occurring in LCA's goal and scope definition and inventory phases. Problems encountered during goal and scope definition arise from decisions about inclusion and exclusion. When defining functional units, one must select the functions to include and settle upon ways to quantify them. Boundary selection requires decisions about including and excluding processes. Exclusion of economic and social impacts in LCA sets fundamental limits on the comprehensiveness of the tool. And, choice of alternative scenarios influences decisions in the interpretation phase. These choices and processes used to make them currently reduce assessment accuracy and introduce uncertainty. Inventory analysis problems involve flows and transformations. The allocation problem results from the need to accurately associate flows from a multi-functional process to each of its functions or the products being assessed. Inappropriately severe cutoff criteria unnecessarily increase data costs while insufficient criteria lead to the exclusion of consequential flows. Local technical uniqueness becomes problematic when average or generic data or models are used to represent processes that significantly differ from the norm.

We invite the reader to continue our examination of LCA's unresolved problems in Part 2 of this paper. The second installment of this two-part review discusses problems arising during impact assessment and interpretation. It includes a review of data quality and availability problems. And, it concludes with an extended summary and suggestions for improving this foundational environmental assessment method for product systems.

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